

**DESIGN OF MICROWAVE BANDPASS FILTER WITH NOVEL
PARALLEL COUPLED GROOVED MICROSTRIP STRUCTURE**

JAYASEELAN MARIMUTHU

UNIVERSITI TEKNOLOGI MALAYSIA

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JAYASEELAN MARIMUTHU

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of the requirements for the award
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Dedicated to My Beloved Father Marimuthu Perumal
Called to the loving arms of our Lord Siva on 7th October 1994

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ABSTRACT

The research consists of two parts. The first part is the derivation of the design equations for parallel coupled bandpass filter whilst the second part is the modification of the structure to improve the 2nd harmonic rejection. Physical dimension equations by Sina Akhtarzad, Thomas R. Rowbotham and Peter B. Johns [18], 1975 were modified to calculate the strip width-to-substrate thickness and like gap-to-substrate thickness ratios from desired values of the even and odd modes characteristic impedances. The modified equations were taken from [12] and [20]. The improved set of equations has accuracy of less than 1.5% and 4% for the even and odd mode characteristic impedances, respectively, compared to [17]. Each length of the coupled region is calculated by using the modified equation of [22]. The designed filter has accuracy of less than 1.64 % and 0.18% for the return and insertion losses, respectively, compared to the design from [17]. Conventional parallel coupled bandpass filter showed very high 2nd harmonic signal at twice the center frequency and asymmetrical response at the upper and lower stop bands. To improve the 2nd harmonic rejection and asymmetrical response at the upper and lower stop bands a modified structure of parallel coupled bandpass filter is proposed. The modified structure is very simple since it does not require recalculation of the physical dimension but showed very good improvement of the 2nd harmonic rejection. The modification was carried out by introducing consecutive square grooves in the arm of the coupled resonator of parallel coupled bandpass filter. The square grooves were placed at equal distance from each other where this ranges from 1 groove up to 7 grooves. The second harmonic present of the in the parallel coupled bandpass filter is due to the different phase velocity experienced by the even and odd modes. For the odd mode, the propagation on in the inner part of the parallel coupled line travels at high phase velocity compared to the even mode which travels at the outer part. By placing the square grooves at the inner part of the parallel coupled, this equalizes the electrical length for the odd and even modes. Hence, the rejection of 2nd harmonic and the improvement in the asymmetrical response were also achieved. The maximum rejection of -100dB for the 2nd harmonic and 30% improvement of the upper cut off frequency have been achieved.

ABSTRAK

Keseluruhan kajian ini terbahagi kepada dua bahagian. Bahagian pertama ialah pembinaan persamaan rekabentuk penapis terganding selari halus jalur. Bahagian kedua ialah pengubahsuaian struktur untuk menghapus kehadiran harmonik kedua. Persamaan fizikal dimensi dari Sina Akhtarzad, Thomas R. Rowbotham and Peter B. Johns [18], 1975 diubahsuai untuk mengira nisbah lebar jalur – ketebalan substratum dan sela jalur – ketebalan substratum dari nilai galangan ciri mod ganjil dan genap. Persamaan ubahsuai diambil dari [12] dan [20]. Persamaan yang diperbaharui mempunyai ketepatan kurang daripada 1.5% dan 4% bagi masing-masing galangan ciri mod genap dan ganjil berbanding [17]. Panjang bahagian terganding dikira menggunakan persamaan terubahsuai daripada [22]. Penapis yang dibina mempunyai ketepatan kurang daripada 1.64 % dan 0.18% bagi masing-masing kehilangan kembali dan sisipan daripada [17]. Penapis jalur halus terganding selari tradisional menunjukkan kehadiran harmonik kedua yang tinggi pada dua kali frekuensi pertengahan dan ketidak simetrian sambutan pada frekuensi jalur henti atas dan bawah. Untuk mengurangkan kehadiran harmonik kedua dan menambahkan kesimetrian sambutan penapis, modifikasi struktur dicadangkan. Modifikasi tersebut memberi kesan pengurangan harmonik kedua yang hebat dan memperbaiki kesimetrian sambutan di mana pengiraan semula tidak diperlukan dan kaedahnya mudah. Modifikasi dilakukan dengan memperkenalkan alur segiempat sama yang sama jarak di antara satu dengan lain pada bahagian penapis terganding selari. Alur ini diperkenalkan dalam bilangan 1 hingga 7. Harmonik kedua wujud pada penapis disebabkan oleh kehadiran mod ganjil dan mod genap. Mod ganjil yang bergerak pada bahagian dalam terganding selari merambat dengan halaju fasa tinggi berbanding dengan mod genap merambat pada bahagian luar terganding selari. Dengan memperkenalkan alur yang sama pada bahagian dalam terganding selari, jarak keelektrikan kedua-dua mod menjadi sama. Oleh itu, kedua-dua mod mempunyai jarak keelektrikan yang sama dan harmonik kedua dapat dikurangkan. Kajian mendapati bahawa harmonik kedua dikurangkan sebanyak -100dB dan frekuensi potong atas dapat diperbaiki sebanyak 30%.

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LIST OF ABBREVIATIONS

BPF	-Bandpass Filter
FBW	-Full Band Width at f_c
TEM	-Transverse Electromagnetic
O.C	-Open Circuit

LIST OF SYMBOLS

β	-Phase Constant
β_e	-Phase Constant of Even Mode
β_o	-Phase Constant of Odd Mode
ϵ_{eff}	-Effective Dielectric Coefficient
ϵ_{effn}	-Average Effective Dielectric Constant for Even and Odd Mode
ϵ_{even}	-Effective Dielectric Constant for Even Mode
ϵ_o	-Permeability of Free Space
ϵ_{odd}	-Effective Dielectric Constant for Odd Mode
ϵ_r	-Dielectric Constant of the Substrate
λ	-Wavelength Length
λ_{even}	-Wavelength of Even Mode
λ_g	-Wavelength of Guided Wave
λ_{gc}	-Wavelength at Design Frequency
λ_{gm}	-Midband Wavelength
λ_{odd}	-Wavelength of Odd Mode
θ	-Length of the Line of the filter matched to Z_o
θ_c	-Electrical Length of the c -mode
θ_π	-Electrical Length of the π -mode
η_o	-Intrinsic Impedance of the Free Space $120\pi \Omega$
ω	-Angular Frequency
ω_o	-Angular Frequency at Center Frequency f_c
ω_1	-First Cutoff Angular Frequency at Center Frequency f_1
ω_2	-Second Cutoff Angular Frequency at Center Frequency f_2
$\Delta\omega$	-Small Changes in Angular Frequency
a_b	-Ripple Factor Butterworth Response Filter

a_c	-Ripple Factor Chebyshev Response Filter
c	-Speed of Light
C	-Equivalent Capacitor for given Z_o and ω_o
C_e	-Total Even Mode Capacitances with Dielectric Coefficient ϵ_r
C_e^o	-Total Even Mode Capacitances Air as Dielectric $\epsilon_r = 1.0$
C_f	-Fringing Capacitance of a Microstripline of Width w/h at Outer Part
C_f'	-Fringing Capacitance of a Microstripline of Width w/h at Inner Part
C_{ga}	-Capacitance in Odd Mode for Fringing Field across the Gap, in Air Region.
C_{gd}	-Capacitance in Odd Mode for Fringing Field across the Gap, in Dielectric.
C'_n	-Equivalent Capacitor for given Z_o , ω_o and g_n
C_o	-Total Odd Mode Capacitances with Dielectric Coefficient ϵ_r
C_o^o	-Total Odd Mode Capacitances Air as Dielectric $\epsilon_r = 1.0$
C_p	-Capacitance between Parallel – Plate with Substrate Dielectric Coefficient ϵ_r
D	-Beat Wavelength of the Perturbation
F	-Fractional Bandwidth of the Filter
f_1	-First cut off Frequency of the Filter at 2.375 GHz
f_2	-Second cut off Frequency of the Filter at 2.625 GHz
f_c	-Center Frequency of the Filter at 2.5 GHz
g	- s/h , Gap to Height Ratio for Parallel Coupled Microstrip Line
g_n	-Prototype Lumped – Element Low – Pass Filter
h	-Height / Thickness of the Dielectric Substrate
IL	-Insertion Loss at $f=1.9$ GHz
I_n	-Current at Port 1
J	- Admittance Inverter
j	-Complex Number Notation ($\sqrt{-1}$)
$J_{z1, even}$	-Current Distribution of the Even Modes at 1 st Microstrip
$J_{z2, even}$	-Current Distribution of the Even Modes at 2 nd Microstrip
$J_{z1, odd}$	-Current Distribution of the Odd Modes at 1 st Microstrip
$J_{z2, odd}$	-Current Distribution of the Odd Modes at 2 nd Microstrip
K_{mn}	-Coupling Coefficient between Two Parallel Microstrip in Interdigital Filter
L	-Equivalent Inductor for given Z_o and ω_o
l	-Length of the Coupled Region / Length of the Microstrip Line
l_c	-Path Length of the c -mode

$l_{corrected}$	-Corrected Length of the Coupled Region
l_e	-Length Due to End Effect
l_π	-Path Length of the π -mode
L'_n	-Equivalent Inductor for given Z_o , ω_o and g_n
n	-Filter Order / Number of Grooves
R_{pb}	-Passband Maximum Insertion Loss Butterworth Response Filter
R_{pc}	-Passband Ripple Chebyshev Response Filter
s	-Gap between Two Parallel Microstrip Lines
S_{11}	-S parameter for port 1 to port 1 (Reflection Coefficient at Port 1)
S_{21}	-S parameter for port 1 to port 2 (Transmission Coefficient Port 1-Port 2)
S_{mn}	-Gap between Two Parallel Microstrip in Interdigital Filter
s/h	-Gap to Substrate Height Ratio for Parallel Coupled Microstrip Lines
t	-Thickness of the Conductor on Top of Dielectric
u	- w/h Width to Substrate Height Ratio for Parallel Coupled Microstrip Line
v_{even}	-Velocity of Even Mode
v_{odd}	-Velocity of Odd Mode
v_p	-Phase Velocity of the Wave
w_o	-Width of the input and output port
w	-Width of the Single Microstrip
w/h	-Width over Height Ratio for Parallel Coupled Microstrip Lines
$(w/h)_{se}$	-Width over Height Ratio for Single Microstrip Line corresponding to Z_{se}
$(w/h)_{so}$	-Width over Height Ratio for Single Microstrip Line corresponding to Z_{so}
$(w/h)'$	- w/h included effect of strip thickness
Y	-Admittance seen at the Input of the Filter
Z_L	-Load Impedance
Z_{mn}	-Impedance of T-Circuit
Z_o	-Characteristic Impedance of Single Microstrip Line / Transmission Line
Z_{oe}	-Even Mode Characteristic Impedance for Parallel Coupled BPF
Z_{oo}	-Odd Mode Characteristic Impedance for Parallel Coupled BPF
Z_{se}	-Equivalent to Single – Line Characteristic Impedance for Even Mode
Z_{so}	-Equivalent to Single – Line Characteristic Impedance for Odd Mode

CHAPTER 1

INTRODUCTION

1.1. Background

Filters are essential in the RF front end of microwave wireless communication system. In planar microstrip and stripline realization, one of the most common implementation methods for bandpass and bandstop filters with required bandwidths up to a 40% of central frequency is to use a cascade of parallel - coupled sections [1], [2].

The synthesis procedure which consists of the design equation for the coupled line physical parameters (space-gap between parallel lines, line widths and lengths) is easy and can be found in any classical microwave books. Based on this, a well-defined systematic procedure, for the required parallel coupled microstrip – filter physical parameters can be easily derived for both Butterworth and Chebyshev response of any order. The filter can be fabricated easily and it exhibits reasonably good performance compared with other planar circuit filters [1].

Although parallel coupled bandpass microstrip – filter is very popular and simple to implement as shown Figure 1.1, the traditional design does suffer from a fundamental limitation, namely, the presence of spurious response at twice the basic passbands at the design frequency as shown Figure 1.2.

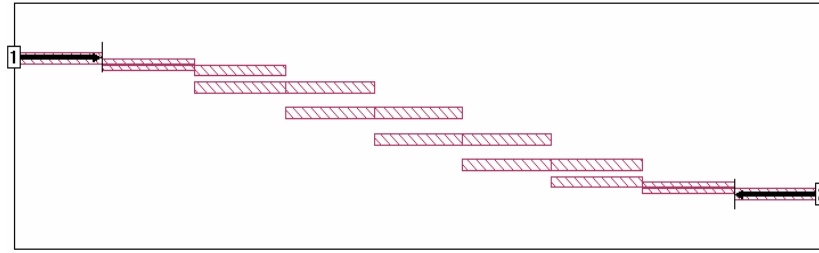


Figure 1.1: Conventional 6th Order Butterworth Parallel – Coupled Line Bandpass Filter

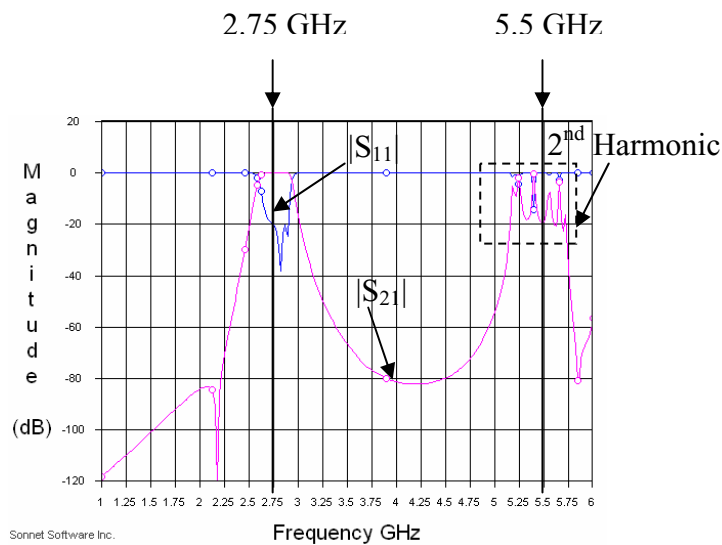


Figure 1.2: The Response of Conventional 6th Order Butterworth Parallel – Coupled Line Bandpass

1.2. Problem Statement

One of the disadvantages is that the first spurious passband of this type of filter appears at twice the basic passband frequency as shown in Figure 1.2. Therefore, the rejection of the upper stopband is worse than that of the lower stopband. For example, if coupled – line filter is used at the next stage of frequency converter, harmonic signals originated from frequency converter still exist. This causes response asymmetry in the upper and lower stop bands. Hence, this greatly limits its applications and degrades system performance.

This is resulted from the inequality of even and odd mode phase velocities of coupled lines in each stage. This problem becomes severe if inverted microstrip and suspended-substrate stripline are used, since these two media exhibit considerably greater difference in mode velocities [3].

Another disadvantage of the parallel-coupled filter is that the filter response shows steeper roll-off on the lower frequency side than on the higher frequency side as seen in Figure 1.2. This is the so-called frequency response asymmetry. The asymmetry is apparent when looking at the response of the passband group delay. The frequency response symmetry is also important in applications involving pulsed signals.

To reject these harmonics, it is usually necessary to cascade additional low pass filters that can reject the spurious passbands. This solution, however, increases the filter layout area and introduces additional insertion losses. Hence, it is necessary to obtain a design technology that can reduce size and reject a harmonic signal.

Many works [3] - [6] have been proposed to tackle this problem. They fall into two categories [4]:

- (i) providing different lengths for even and odd modes,
- (ii) equalizing the modal phase velocities.

It is found that connecting a short uncoupled line section at either end of the coupled section improves filter characteristics, if section lengths are chosen correctly [3]. An over coupled resonator is proposed to extend phase length for the odd mode to compensate difference in the phase velocities. Subsections with a coupled three-line microstrip are inevitable at both ends of each coupled section in the filter [4].

The capacity compensated structures are also effective in suppressing the spurious passband at $2f_c$. It should be noted that the loading capacitor are subject to

the electrical parameters of each coupled section [5], [6]. Recently, combinations of different stripline-stepped impedance resonators (SIR) with specified coupling angles can suppress the spurious response [7].

The gap size and the line width for the input/output-coupled resonators are reduced to improve the rejection at $2f_c$ [8]. Coupled wiggly microstrip lines also show an effective suppression on the spurious passband. The strip-width perturbation does not require the filter parameters to be recalculated, and the classical design methodology for coupled-line microstrip filters can still be used [9].

Based on [9], a modified structure is proposed by applying the general ideas of the above – mentioned and Bragg condition to microstrip line to improve harmonic suppression characteristics [10].

1.3. Proposed Design

The modified structure proposed is shown in Figure 1.4; using conventional parallel coupled – line bandpass filters, bragg and non - bragg condition to coupled section of microstrip line to improve harmonic suppression and frequency response symmetry for lower cut off and upper cut off frequency characteristics without recalculating the physical dimension of the design.

The proposed design was chosen because of the simplicity and well known design methodology. Well established design equations are available and equations are simple for physical design parameter. The modification does not require recalculation of design parameters such as space – gap between parallel lines, line widths and lengths as shown in Figures 1.3 and 1.4. The structure is also easy to be fabricated.

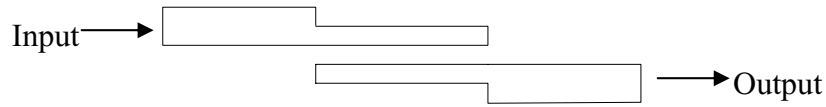


Figure 1.3: Non-Modified Conventional Parallel – Coupled Line Bandpass Filter.

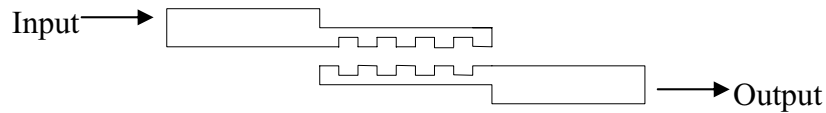


Figure 1.4: Modified Conventional Parallel – Coupled Line Bandpass.

1.4. Characteristic of Improved Design

In any pair of symmetric coupled microstrip lines, as shown in Figure 1.3, the odd mode propagates faster than the even mode along the pair, i.e., phase constant for the odd mode is less than the phase constant of the even mode $\beta_o < \beta_e$. To modify the propagation velocity of even and odd mode, a symmetric coupled section with identical physical dimension should be modified for identical electrical lengths by the traveling path for the odd mode should be extended or for even mode should be reduced. For symmetric coupled microstrips lines, the typical current distributions of the odd and even modes are shown in Figure 1.5. It shows that the electromagnetic energy for the odd mode concentrates around the center gap, while for the even mode, it concentrates around the outer metallic edges.

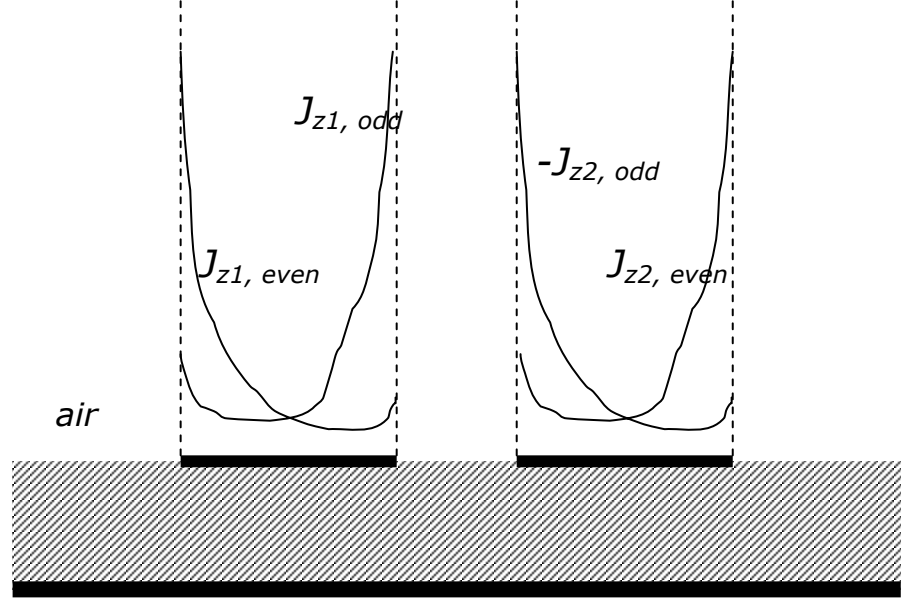


Figure 1.5: Current Distribution of the Odd – and Even – Modes of a Pair of Symmetric Coupled Microstrip [11].

The possible and simplest way to extend the electrical path for the odd mode, and at same time to increase that for the even mode to a minim extent, is to modify the flat coupled lines to corrugated coupled lines by introducing square grooves at periodical order as shown in Figure 1.4.

Due to the modification, the symmetric coupled microstrip lines no longer symmetric with respect to the propagation direction. The even and odd modes of symmetric coupled lines are perturbed and turn into c – mode and π – mode, respectively. Most of the energy of the π – mode will travel along the central wiggle coupling slot will experience periodical changes in propagation direction, while that of the c – mode along the straight outer metallic edges does not experience any changes in propagation direction. Based on that, the total electrical lengths of these two eigen – modes in a coupled section can be equalized, i.e., $\theta_c = \theta_\pi$, since the path length $l_c > l_\pi$ and phase constant $\beta_c > \beta_\pi$.

1.5. Parallel – Coupled – Line Filter Design Specification

The design parameters chosen are 3rd to 9th order Butterworth and Chebyshev response bandpass filters centered at $f_c = 2.5$ GHz with 10 % fractional bandwidth, substrate dielectric constant is $\epsilon_r = 10.2$ Figure 1.6 shows substrate thickness $h = 1.27$ mm and metal layer thickness $t = 0.017$ mm.

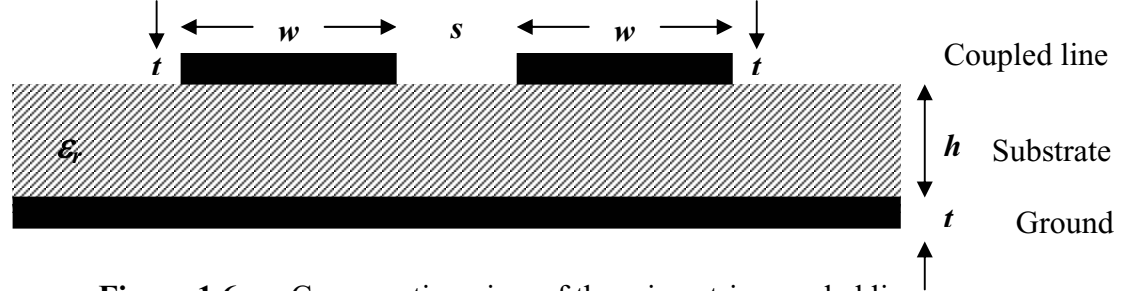


Figure 1.6: Cross section view of the microstrip coupled line.

The design parameters are chosen for two different responses at various orders to prove the applicability of the modified filter regardless of filter response type and order of the filter.

1.6. Objectives

The main goal of this research is to design, simulate and analyze modified structures of conventional parallel – coupled bandpass filter without recalculating the physical dimension, which improve the performance of filter, by minimizing spurious response at harmonic ($2f_c$) (improving the suppression performance of 2nd harmonic signal) and frequency response symmetry for lower cut off and upper cut off frequency characteristics.

1.7. Scopes

The scope of this project is divided into several parts; the first part is to identify the design equations for conventional parallel – coupled – line bandpass filter. Based on the design equations, MathCAD files are developed to calculate the physical parameters for conventional parallel – coupled – line bandpass filter. The filter responses based on the various design equations are compared and analyzed.

The second part is based on the chosen design equation in the first part, design conventional parallel – coupled – line bandpass filter for Butterworth and Chebyshev responses for the 3rd to 9th Order. The designs are simulated using Sonnet release 9 and analyzed.

The third part, is the improvement of the filter performance by modifying the conventional parallel – coupled bandpass filter structure by introducing number of grooves from 1 to 7 in all the design above, simulate the designs. The structures are simulated and analyzed.

A comparison study was carried out for the modified and non – modified structures for the parallel coupled bandpass filter from the second and third part. Finally based on the modified structures, optimized filter is determined which as minimum harmonic response and fulfilled the design specifications.

1.8. Overview on the Thesis Organization

Chapter 1 provides a first glimpse at the basic aspects of the research undertaken; introduction, problem statement, proposed design, characteristics of the improved design, parallel – coupled – line filter design specification, objectives as well as the scopes of the research.

Chapter 2 gives an overview of the fundamentals of parallel coupled bandpass filter design equations in terms of filter specifications. It also shows how a parallel coupled can be used for the filter design, based on the given specification how to obtain the Z_{oe} and Z_{oo} from lowpass filter prototype elements. Various methods utilized to reduce the second harmonic are investigated and comments are given.

Chapter 3 shows the detail studies of various types of design equations and modifications on the design equations. Careful and detail studies were carried out on chapter to obtain a right design equation. Finally an appropriate design equation was achieved and used for further design of the parallel coupled bandpass filter. Filter design parameters are presented for various orders and responses for parallel coupled bandpass filter center frequency 2.5 GHz with operation bandwidth of 10 %.

In chapter 4, results and discussion are presented. Based on the design equation from chapter 3, the design modification was introduced on the parallel coupled bandpass filter and simulated. The complete results are given for non modified and modified filters.

From the results and discussion of chapter 4, further modification has been done on the filter design parameter to achieve the actual design specification proposed in this research. The modification is carried out for various orders and responses. Finally, the results are presented and discussed.

Chapter 6 concludes the thesis followed by recommendations for future work.